# MSSM Charged Higgs from Top Quark Decays


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based on works done in collaboration with:
Boos, Buchinev, J. Ellis, Espinosa, Garcia, Haber,
J.-S. Lee, Quiros, Mrenna, Pilaftsis, Nierste, and Wagner

**Standard Model → effective theory**

**Supersymmetry → interesting alternative BSM**

If SUSY exists, many of its most important motivations
demand some SUSY particles at the TeV range or below

1. solve the hierarchy problem
2. generate EWSB by quantum corrections
3. Allow for gauge coupling unification at a scale $\approx 10^{16}\,\mathrm{GeV}$
4. induce a large top quark mass from Yukawa coupling evolution.
5. provide a good dark matter candidate: the lightest neutralino
6. provide a possible solution to baryogenesis

**Minimal model: 2 Higgs SU(2) doublets 5 physical states:**

| | | |
|---|---|---|
| **2 CP-even** | **h, H** | **with mixing angle** $\alpha$ |
| **1 CP-odd** | **A** | **and a charged pair** $H^{\pm}$ |

★ Higgs Physics: important tool in understanding Supersymmetry

# MSSM Higgs sector at Tree-Level

$H_1, H_2$ doublets $\Longrightarrow$ 2 CP-even Higgs h, H    1 CP-odd state A    2 charged Higgs $H^\pm$

Higgs masses and couplings given in terms of two parameters:

$m_A$ and $\tan\beta \equiv v_2/v_1$    mixing angle $\alpha \Longrightarrow \cos^2(\beta-\alpha) = \frac{m_h^2(m_Z^2-m_h^2)}{m_A^2(m_H^2-m_h^2)}$

Couplings to gauge bosons and fermions (norm. to SM)

hZZ, hWW, ZHA, $WH^\pm H$ $\longrightarrow \sin(\beta-\alpha)$

HZZ, HWW, ZhA, $WH^\pm h$ $\longrightarrow \cos(\beta-\alpha)$

(h,H,A) $u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$

(h,H,A) $d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$

$$g_{H^-t\bar{b}} = \frac{\sqrt{2}}{\mathrm{v}}\left[m_t \cot\beta\, \mathrm{P_R} + m_b \tan\beta\, \mathrm{P_L}\right]; \quad g_{H^-\tau^+\nu} = \frac{\sqrt{2}}{\mathrm{v}}\left[m_\tau \tan\beta\, \mathrm{P_L}\right]$$

If $m_A \gg M_Z$

$\Downarrow$

decoupling limit

- $\cos(\beta-\alpha)=0$    up to correc. $\mathcal{O}(m_Z^2/m_A^2)$
- lightest Higgs has SM-like couplings and mass $m_h^2 \simeq m_Z^2 \cos^2 2\beta$
- other Higgs bosons: heavy and roughly degenerate

$m_A \simeq m_H \simeq m_H^\pm$    up to correc. $\mathcal{O}(m_Z^2/m_A^2)$

# Radiative corrections to Higgs Masses

**After quantum corrections, Higgs mass shifted due to incomplete cancellation of particles and superparticles in the loops**


Main effects: top and stop loops; bottom and sbottom loops for large tanb

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2}\left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \mathrm{h.o.}$$

$$M_S^2 = \tfrac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) \text{ and } X_t = A_t - \mu/\tan\beta$$

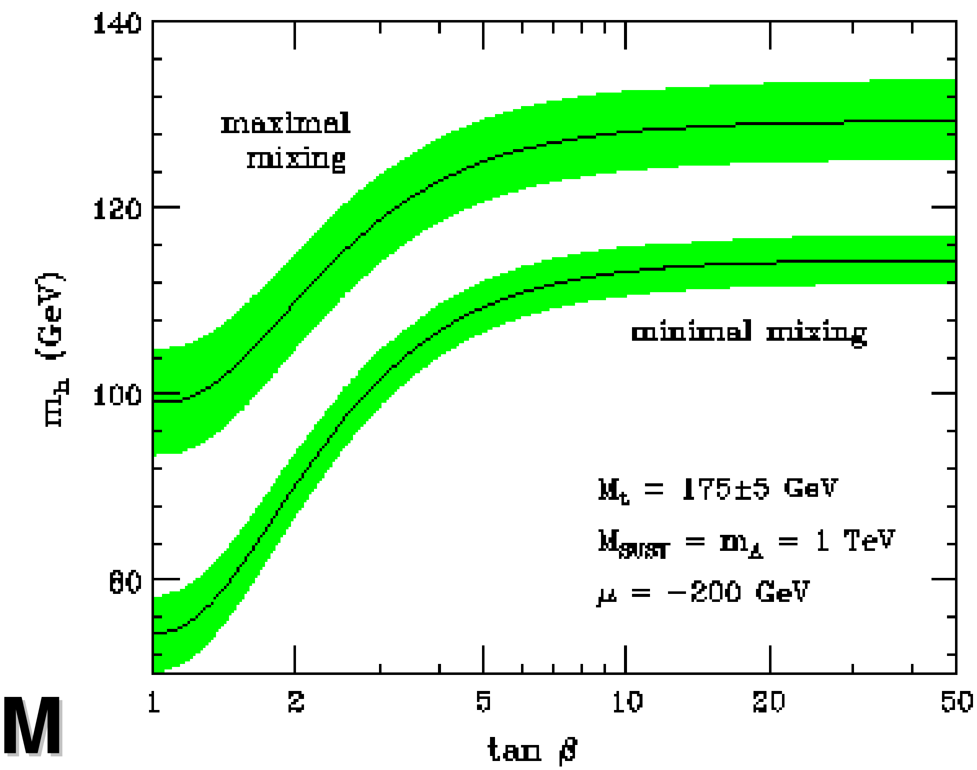
**Main Quantum effects:**

**$m_t^4$ enhancement ; dependence on stop mixing $X_t$ and logarithmic sensitivity to $M_S$**

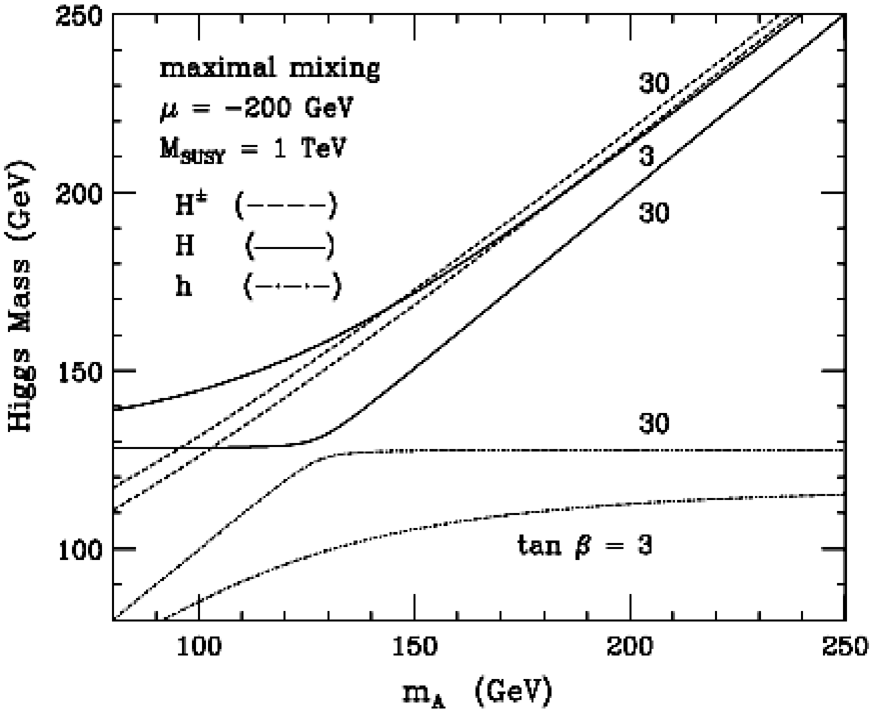
**Upper bound :**

$$m_h \leq 135 \text{ GeV}$$

**stringent test of the MSSM**



# MSSM Higgs Masses as a function of $M_A$




$$m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta-\alpha) \to 1$ for large $\tan\beta$, low $m_A$
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta-\alpha) \to 1$ for large $m_A$
  $\Longrightarrow$ h has SM-like couplings to W,Z

for large $\tan\beta$:
always one CP-even Higgs with SM-like couplings to W,Z
and mass below $m_h^{max} \lesssim 135$ GeV

Mild variation of the charged Higgs with SUSY spectrum

## LEP MSSM HIGGS limits:

$m_h > 91.0\text{GeV};$ $\quad m_A > 91.9\text{GeV};$ $\quad m_{H^{\pm}} > 78.6\text{GeV}$

$m_h^{\text{SM-like}} > 114.6\text{GeV}$

# Radiative Corrections to Higgs Couplings

$\boxed{1}$ Through rad. correc. to the CP-even Higgs mass matrix, $\delta\mathcal{M}^2_{ij}$, which defines the mixing angle $\alpha$

$$\sin\alpha\cos\alpha = \mathcal{M}^2_{12} \,/\, \sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\,\det\mathcal{M}^2}$$

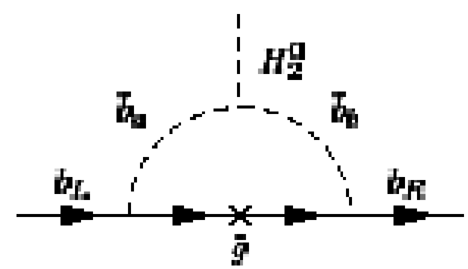
important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on sign of $\mu\, A_t$ and magnitude of $A_t/M_S$.

$\Longrightarrow$ govern couplings of Higgs to fermions

$\Longrightarrow$ via rad. correc. to $\underline{\cos(\beta-\alpha)\text{ and }\sin(\beta-\alpha)}$ governs Higgs couplings to vector bosons

$\boxed{2}$ SUSY vertex correc. to Yukawa couplings, which modify the effective Lagrangian, coupling Higgs to fermions

$$\mathcal{L}_{\rm eff} \longrightarrow h_b\, H_1^0\, b\bar{b} + \Delta h_b\, H_2^0\, b\bar{b}$$



$\Delta h_b$ modifies the $m_b$–$h_b$ relation

$$m_b \simeq h_b v_1 + \Delta h_b v_2 = h_b\, v\, \cos\beta \left(1 + \frac{\Delta h_b}{h_b}\tan\beta\right)$$

$$\Delta_b = \frac{\Delta h_b}{h_b}\tan\beta \sim \frac{2\alpha_S}{3\pi}\,\frac{\mu\, M_{\tilde{g}}}{\max(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}})}\,\tan\beta + \Delta_b^{\tilde{t}\tilde{\chi}^+}$$

$\Delta_b \sim \mathcal{O}(1)$ if $\tan\beta$ large

$$\Delta_b^{\tilde{t}\tilde{\chi}^+} \sim \frac{h_t^2}{16\pi^2}\,\frac{\mu\, A_t}{\max(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)}\,\tan\beta$$

More generally we can write the Effective Lagrangian:

$$-\mathcal{L}_{\rm eff} = \epsilon_{ij}\left[(h_b+\delta h_b)\bar{b}_R H_d^i Q_L^j + (h_t+\delta h_t)\bar{t}_R Q_L^i H_u^j\right] + \Delta h_t \bar{t}_R Q_L^k H_d^{k*} + \Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \text{h.c.}$$

The resulting interaction Lagrangian defining the couplings of the physical Higgs bosons to third generation fermions:

$$\mathcal{L}_{\rm int} = -\sum_{q=t,b,\tau}\left[g_{hq\bar{q}}hq\bar{q} + g_{Hq\bar{q}}Hq\bar{q} - ig_{Aq\bar{q}}A\bar{q}\gamma_5 q\right] + \left[\bar{b}g_{H^- t\bar{b}}tH^- + \text{h.c.}\right].$$

$$g_{h\,b\bar{b}} \simeq \frac{-\sin\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\left(1-\Delta_b/\tan\alpha\tan\beta\right) \qquad g_{H\,b\bar{b}} \simeq \frac{\cos\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\left(1-\Delta_b\tan\alpha/\tan\beta\right)$$

$$g_{A\,b\bar{b}} \simeq \frac{m_b}{v(1+\Delta_b)}\tan\beta$$

Similarly, $g_{(h/H/A),\tau^+\tau^-}$ replacing $m_b \to m_\tau$, $\Delta_b \to \Delta_\tau$

and $g_{(h/H/A),t\bar{t}}$ replacing $m_b \to m_t$, $\Delta_b \to \Delta_t$, $\tan\beta, \tan\alpha \to 1/\tan(\beta), 1/\tan(\alpha)$ (no $\tan\beta$ enhancement in $\Delta_t$; $\Delta_\tau \ll \Delta_b$)

For the charged Higgs one has important radiative corrections for large tanb

$$g_{H^- t\bar{b}} \simeq \left\{\frac{m_t}{v}\cot\beta\left[1-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}\tan\beta\right]P_R + \frac{m_b}{v}\tan\beta\left[\frac{1}{(1+\Delta_b)}\right]P_L\right\}$$

also $\Delta m_\tau$ corrections in $g_{H^-\tau\nu_\tau}$ may be included.

# Important modifications of coupling due to radiative corrections: depending on MSSM parameter space

$\longrightarrow$ dep. on sign and values of $\mu A_t$, $\mu A_b$, $\mu M_{\tilde{g}}$ and magnitudes of $M_{\tilde{g}}/M_S$, $\mu/M_S$

- destroy the basic relation: $g_{h\,b\bar{b}}/g_{h\,\tau\tau} \sim m_b/m_\tau$

- strong suppression of coupling of $h$ $(H)$ to bottoms if

  $\tan\alpha \simeq \Delta_b/\tan\beta$ $\qquad ((\tan\alpha)^{-1} \simeq -\Delta_b/\tan\beta)$

  $g_{h\,b\bar{b}} \simeq 0$ ; $g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v}\Delta_b$ $\qquad$ (h $\leftrightarrow$ H)

$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $\quad b\bar{b} \sim 80\%$ $\quad \tau^+\tau^- \sim 7-8\%$

*drastically changed* $\Longrightarrow$ other decay modes enhanced

- strong suppresion/enhancement of the charged Higgs coupling to top-bottom depending on sign of $\Delta_b = \frac{\Delta h_b}{h_b}\tan\beta$, ➔ sign of mu for positive gluino mass

- Similar behaviour for the CP-odd higgs b-b coupling

# Renormalization Group Effects

- tanb enhanced correc. to $h_b$ are not the only universal ones
- Standard QCD corrections to transitions involving $\bar{t}_L b_R H^+$ Yukawa interactions➔ $\log(Q/m_b)$

-- Summation to all orders in leading logs $\alpha_s^n \log^n(Q/m_b)$ done evaluating running $h_b(Q)$ ⟺ $m_b(Q)$

-- Full one-loop QCD correc. to decay rates require summation of NLO logs $\alpha_s^{n+1}\log^n(Q/m_b)$ due to non-log $\alpha_S$ terms

To consider both effects: using OPE + RG evolution in $\overline{\mathrm{MS}}$

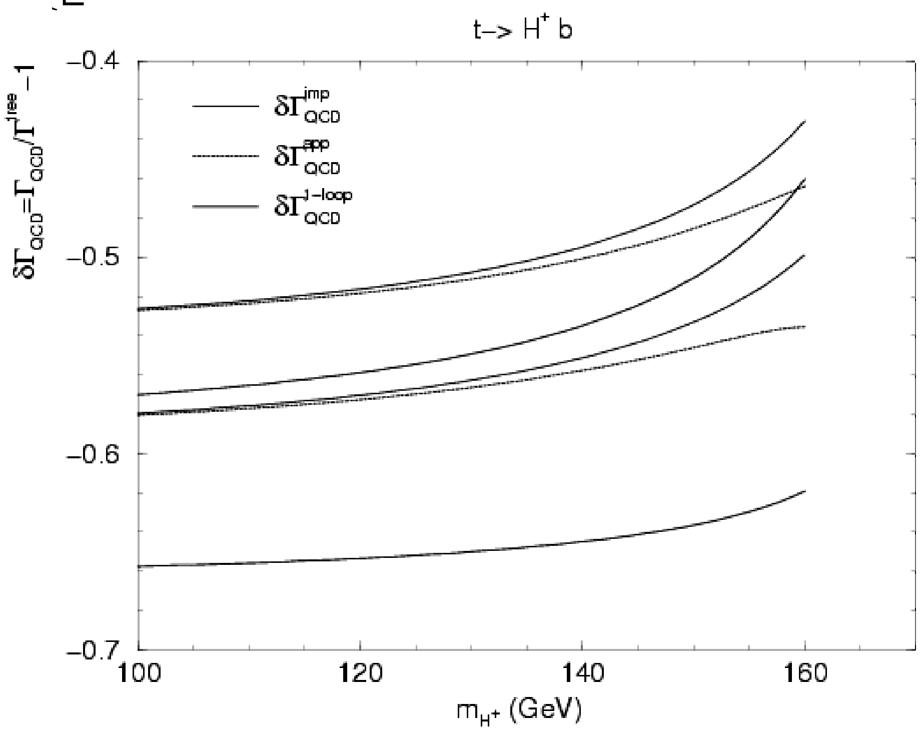
$$\bar{\mathrm{h}}_{\mathrm{b}}(Q=m_b) = \frac{\overline{m}_b(Q=m_b)}{\mathrm{v}} \frac{1}{1+\Delta m_b(Q=M_{SUSY})} \tan\beta$$

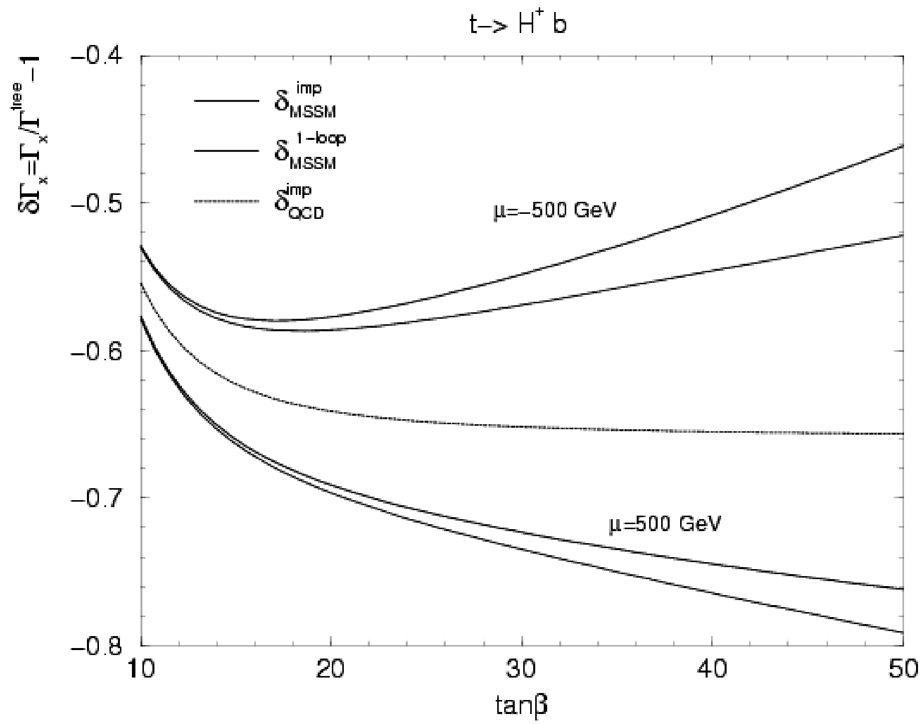
with Q the caracteristic scale of the process

# Quantum Corrections to $\Gamma\left(t \to bH^+\right)$

- leading and subleading log(Q/mb) resummed using mb running in $\Gamma^0$
- One-loop finite QCD terms also included

$$\Gamma^{imp.}_{QCD}(t \to bH^+, \tan\beta \geq 10) = \frac{g^2}{64\pi M_W^2} m_t (1-q_{H^+})^2 \overline{m}_b^2(m_t^2) \tan^2\beta \times \left\{ 1 + \frac{\alpha_s(m_t^2)}{\pi} \times \left[ 7 - \frac{8\pi^2}{9} - 2\log(1-q_{H^+}) + 2(1-q_{H^+}) + \left( \frac{4}{9} + \frac{2}{3}\log(1-q_{H^+}) \right)(1-q_{H^+})^2 \right] \right\}$$



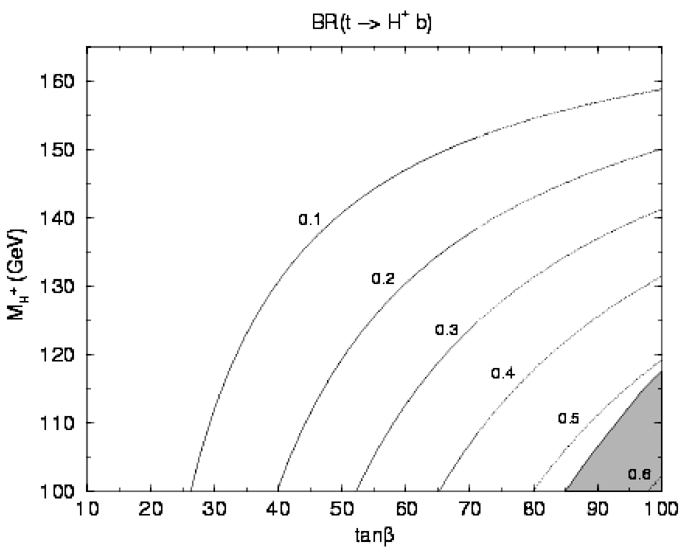



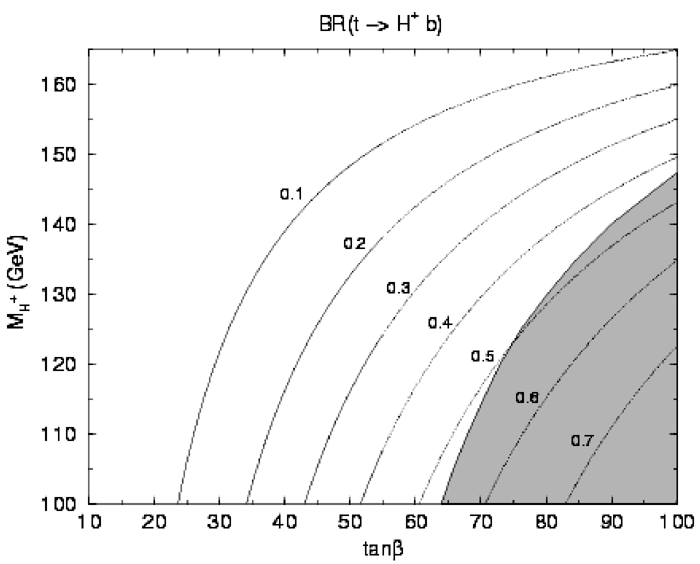

➔ After higher order tanb enhanced SUSY corrections included:

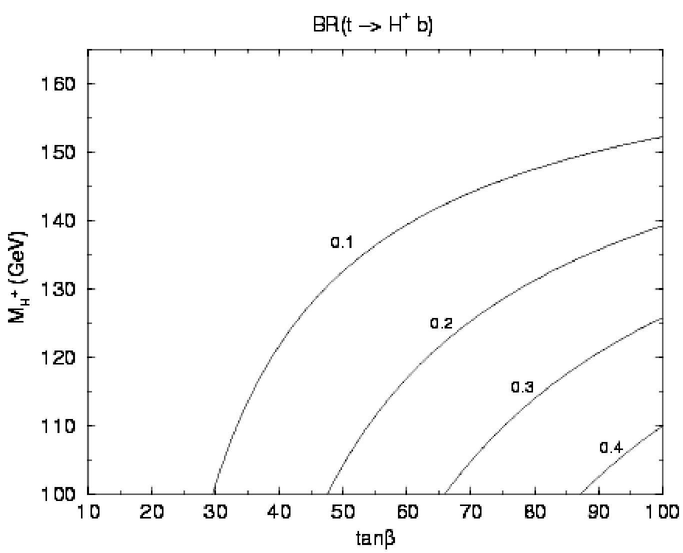
$$\Gamma^{imp.}_{MSSM}(t \to bH^+, \tan\beta \geq 10) = \Gamma^{imp.}_{QCD} \frac{1}{(1+\Delta m_b)^2}$$

# Charged Higgs Searches at theTevatron

## (a RunI example soon to be improved: Eusebi et al. (CDF) in prep.)



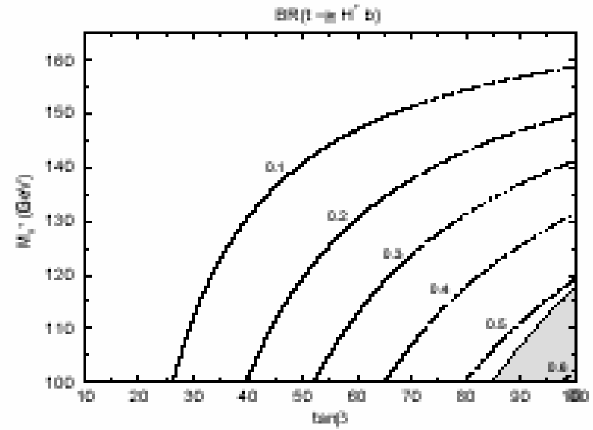



# Charged Higgs searches at the Tevatron

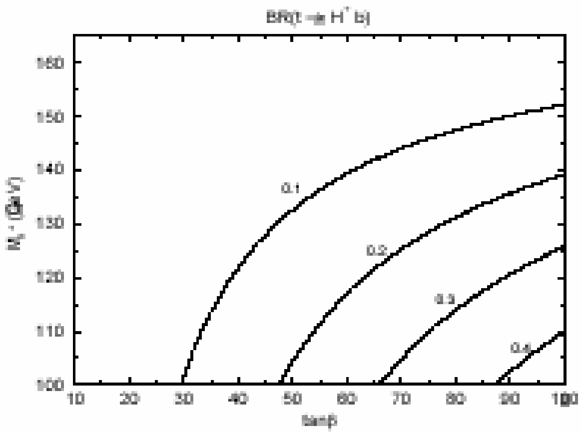
- Curves of constant BR for $t \to bH^+$ after resummation of LO and NLO logarithms of QCD corrections included applying OPE

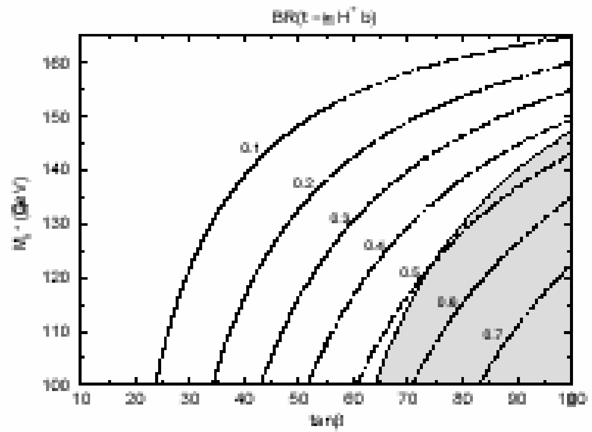
  Shaded area excluded by Run1 DØ frequentist analysis from $H^\pm$ searches in top decays



- Including dominant SUSY correc. for large $\tan\beta$ and a heavy SUSY spectrum

based on $\mathcal{L} \simeq \frac{g}{\sqrt{2}M_W} \frac{\bar{m}_b(Q)\tan\beta}{1+\Delta m_b} \left[V_{tb}H^+\bar{t}_L b_R(Q) + \text{h.c.}\right] \Longrightarrow \Gamma_{MSSM} \simeq \frac{\Gamma^{imp.}_{QCD}}{(1+\Delta mb)^2}$

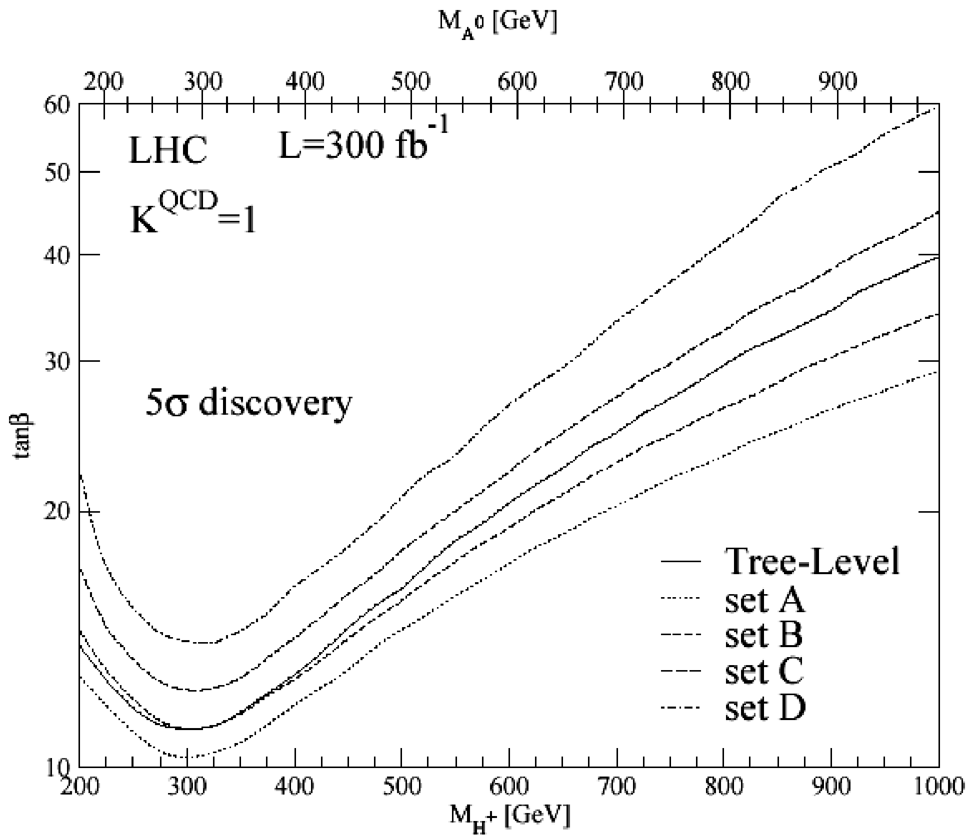




Drastic variations on $\tan\beta - m_{H^\pm}$ plane bounds, depending on MSSM parameter space

M.C., Garcia, Nierste, Wagner

## Similar analysis for $pp \to H^+ tb + X$ at LHC for large $\tan\beta$




Discovery reach at the LHC for different sets of SUSY parameters, which can enhance or suppress the $H^{\pm}tb$ coupling

Discovery reach at LHC with 300 fb$^{-1}$ and $\tan\beta > 30$

- best case scenario: $m_{H^+} \leq 1$ TeV
- worst case scenario: $m_{H^+} \leq 450$ GeV

Belyaev, Garcia, Gausch, Sola

# Tau Polarization & Charged Higgs Measurements

- In the range $m_{H^+} < m_t \Rightarrow \mathrm{BR}(\mathrm{H}^\pm \to \tau^+\nu / \tau^-\overline{\nu}) \approx 1$

it seems difficult to identify $\mathrm{H}^\pm \to \tau\nu$ decays from $\mathrm{W}^\pm \to \tau\nu$

Crucial Observation:

$$\mathrm{W}^- \to \tau_L^- \overline{\nu}_R \qquad (\mathrm{W}^+ \to \tau_R^+ \nu_L)$$

Due to the lefthandness of the charged current: $L \propto W^- \overline{e}_L \gamma_\mu \nu_L + h.c.$

whereas

$$\mathrm{H}^- \to \tau_R^- \overline{\nu}_R \qquad (\mathrm{H}^+ \to \tau_L^+ \nu_L)$$

➔ a consequence of the helicity-flip (conserving) of the SM Higgs (vector boson) couplings

Hence: $P_\tau^H = +1 \qquad P_\tau^W = -1$

This holds in general in models with $\nu_L$ and $\overline{\nu}_R$ only

By convention: $\mathrm{P}_\tau \equiv \mathrm{P}_{\tau^-} = -\mathrm{P}_{\tau^+}$

$$\mathrm{P}_{\tau^\mp} = \frac{\sigma_{\tau^\pm_\mathrm{R}} - \sigma_{\tau^\pm_\mathrm{L}}}{\sigma_{\tau^\pm_\mathrm{R}} + \sigma_{\tau^\pm_\mathrm{L}}}$$

- The decay distributions of the $\tau_R^-$ are sufficiently different from those of $\tau_L^+$

Considering the main contributions to one-prong hadronic tau decays:

$$\tau^\pm \to \pi^\pm \nu_\tau \ (12.5\%);$$

$$\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau \ (24\%) \qquad \tau^\pm \to a_1^\pm \nu_\tau \to \pi^\pm \pi^0 \pi^0 \nu_\tau \ (7.5\%)$$

The dependence of the tau polarization of the angular distributions of the primary decay modes in the tau rest frame

$$\frac{1}{\Gamma_\pi}\frac{d\Gamma_\pi}{d\cos\theta} = \frac{1}{2}\left(1 + \mathrm{P}_\tau \cos\theta\right)$$

$$\frac{1}{\Gamma_{\mathrm{vL}}}\frac{d\Gamma_{\mathrm{vL}}}{d\cos\theta} = \frac{m_\tau^2/2}{m_\tau^2 + 2m_\mathrm{v}^2}\left(1 + \mathrm{P}_\tau \cos\theta\right)$$

$$\frac{1}{\Gamma_{\mathrm{vT}}}\frac{d\Gamma_{\mathrm{vT}}}{d\cos\theta} = \frac{m_\mathrm{v}^2}{m_\tau^2 + 2m_\mathrm{v}^2}\left(1 - \mathrm{P}_\tau \cos\theta\right)$$

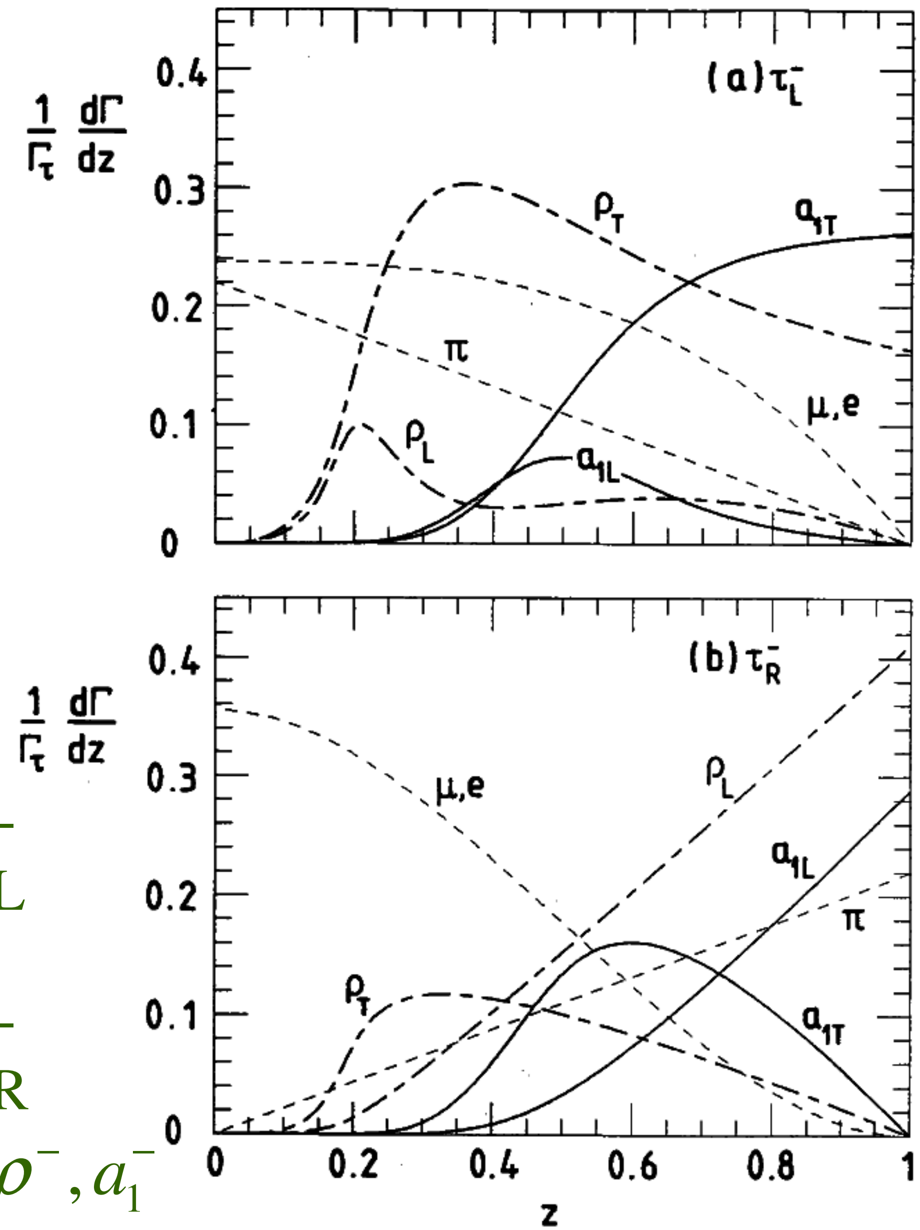
all three channels have an important dependence on $\mathrm{P}_\tau$

For this study I will only use $\tau^\pm \to \pi^\pm \nu_\tau$

## In the colinear limit $E_\tau / m_\tau >> 1$

$$\frac{1}{\Gamma_\tau}\frac{d\Gamma_\pi}{dz} \approx BR_\pi[1+P_\tau\,(2z-1)]\,; \qquad z = \frac{E_\pi}{E_\tau}$$

Energy distributions arising from $W^- \to \tau_L^- \to h^-$ are significantly different from $H^- \to \tau_R^- \to h^-$ decays




- Most energetic particles from $\tau_L^-$ decays ➔ transv. polarized $\rho^-, a_1^-$
- Most energetic particles from $\tau_R^-$ decays ➔ $\pi^-$ & long. polarized $\rho^-, a_1^-$

Energetic pions favour charged Higgs over W's

# Charged Higgs searches at the ILC: the impact of tau Polarization

- We consider $e^+e^- \to t\bar{t} \to W^{\pm} b\, H^{\mp}\, \bar{b}$

  ➔ with $W \to 2\,\text{jets}$

  ➔ and $H^{\mp} \to \tau^{\mp}\nu$

$\sqrt{s} = 500\,\text{GeV}$ and $500\,\text{fb}^{-1}$

Main background: both tops decay into Wb and $W^{\mp} \to \tau^{\mp}\nu$

- Simulations done with CompHEP, including ISR and beamstrahlung with polarized $\tau$
- Polarized $\tau$ decays with TAUOLA, using new CompHEP-TAUOLA interfase (E. Boos et al.)
- All other stages done with CompHEP-Pythia interface
- **Energy distributions are given in the reconstracted top rest frame using the recoil mass technique**

- In the top rest frame:

$$\mathrm{t} \to \mathrm{bR} \to \mathrm{b}\tau\nu_\tau \to \mathrm{b}\nu_\tau\bar{\nu}_\tau\pi$$

where the resonance R is ether the W boson or the charged Higgs

$$\frac{1}{\Gamma_R}\frac{\mathrm{d}\Gamma_R}{\mathrm{d}y_\pi} = \frac{1}{(x_{\max} - x_{\min})} \times$$

$$\begin{cases} (1-\mathrm{P}_\tau)\log\dfrac{x_{\max}}{x_{\min}} + 2\mathrm{P}_\tau y_\pi \left(\dfrac{1}{x_{\min}} - \dfrac{1}{x_{\max}}\right), & \text{if} \quad 0 < \mathrm{y}_\pi < x_{\min} \\ (1-\mathrm{P}_\tau)\log\dfrac{x_{\max}}{y_\pi} + 2\mathrm{P}_\tau \left(1 - \dfrac{y_\pi}{x_{\max}}\right), & \text{if} \quad \mathrm{x}_{\min} < \mathrm{y}_\pi \end{cases}$$

where:

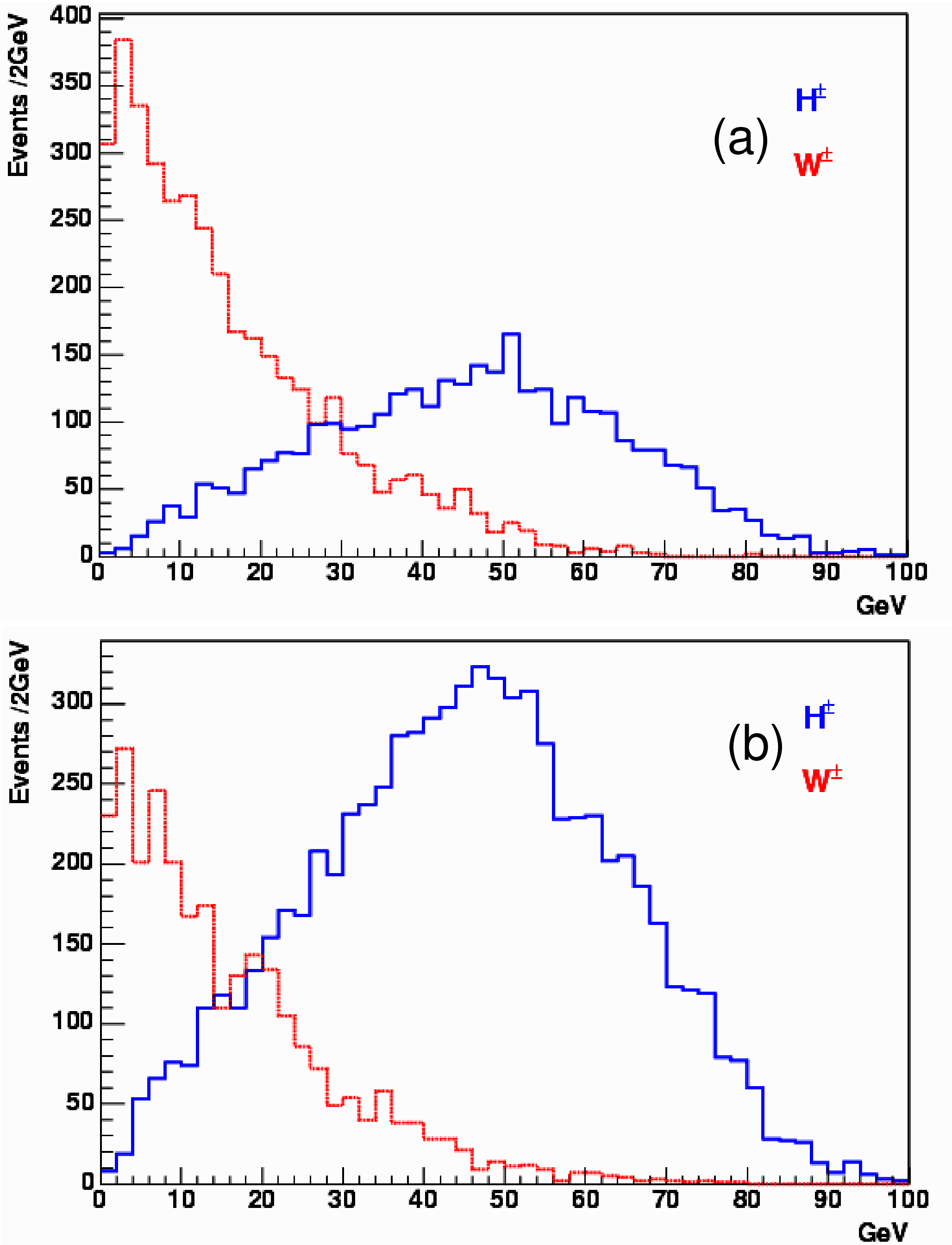
$$y_\pi = \frac{E_\pi^{top}}{m_{top}}, \quad x_{\min} = \frac{E_\tau^{\min}}{m_{top}}, \quad x_{\max} = \frac{E_\tau^{\max}}{m_{top}}, \quad E_\tau^{\min} = \frac{M_R^2}{2m_{top}}, \quad E_\tau^{\max} = \frac{m_{top}}{2}$$

$$\text{Recall:} \quad \mathrm{P}_\tau^{\mathrm{W}} = -1 \quad \text{and} \quad \mathrm{P}_\tau^{\mathrm{H}} = 1$$

M. Nojiri: Boos, Martyn,Moortgat-Pick, Sachwitz, Sherstnev and Zerwas

**for stau pair production: (R equiv. stau)**

# $\pi$ -meson energy spectrum in the top rest frame




Two MSSM benchmark

MSSM scenarios:

common parameters:

$$M_Q = M_U = M_D = M_{\tilde{g}} = M_2 = 1\,\mathrm{TeV}$$

$$A_t = 500\,\mathrm{GeV}$$

$$\tan\beta = 50 \qquad m_{H^\mp} = 130\,\mathrm{GeV}$$

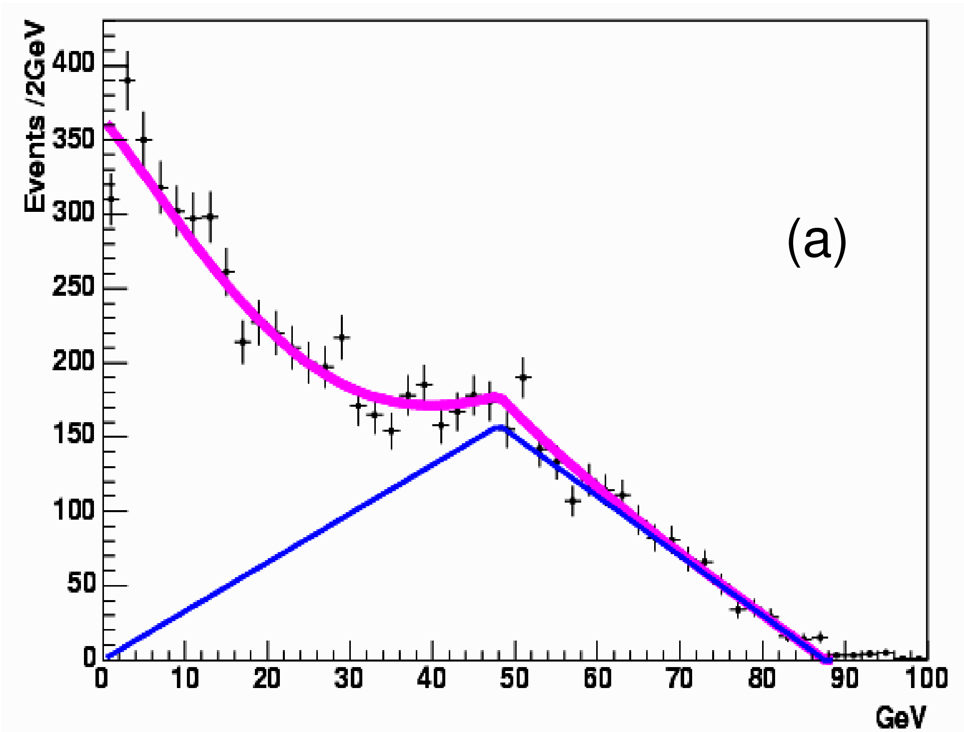
a) $\mu = 500\,\mathrm{Gev}$

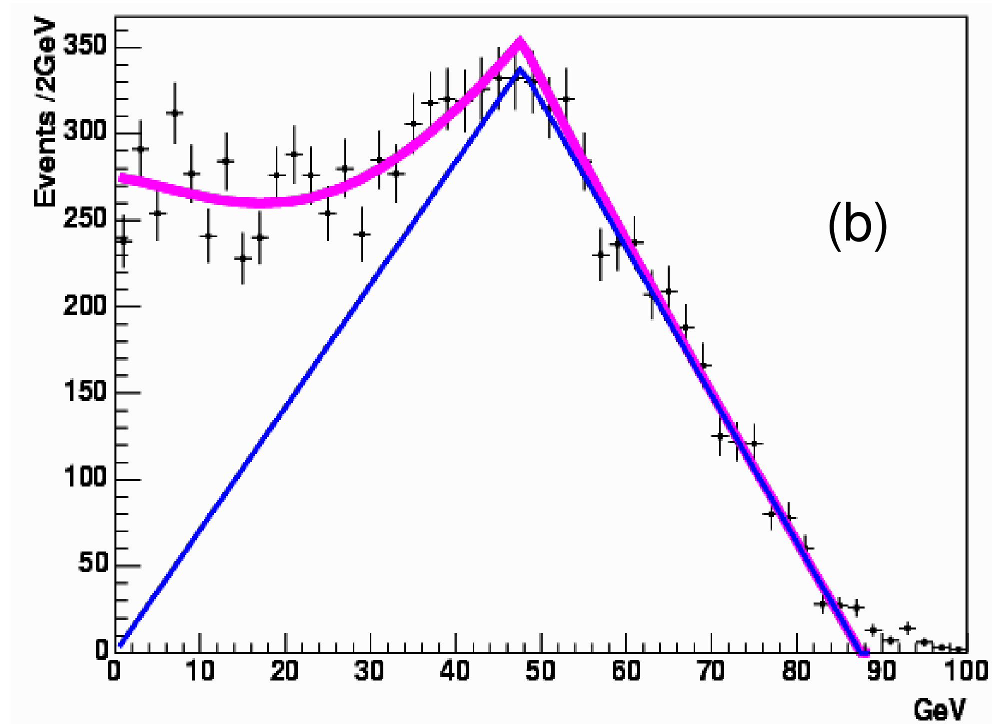
$\Rightarrow \mathrm{BR}(t \to H^+ b) = 10\,\%$

b) $\mu = -500\,\mathrm{Gev}$

$\Rightarrow \mathrm{BR}(t \to H^+ b) = 24\,\%$

# Performing a fit to the simulated signal + background




one can determine the value of $x^H_{\min} = m^2_{H^\mp} / 2 m^2_{top}$

In particular we obtain:

a) $m_{H^\mp} = (129.4 \pm 0.9)$ GeV

b) $m_{H^\mp} = (129.7 \pm 0.5)$ GeV

(no systematics/detector effects)

# CPsuperH

- Code to compute Higgs spectrum, couplings and decay modes in the presence of CP-violation

  Lee, Pilaftsis, M.C., Choi, Drees,Ellis, Lee,Wagner.'03

- CP-conserving case: Set phases to zero. Similar to HDECAY, but with the advantage that charged and neutral sector treated with same rate of accuracy.

- Combines calculation of masses and mixings by M.C., Ellis, Pilaftsis, Wagner. with analysis of decays by Choi, Drees, Hagiwara, Lee and Song.

- Available at

  http://theory.ph.man.ac.uk/~jslee/CPsuperH.html

# Conclusions

- Low energy supersymmetry has an important impact on Higgs physics.

- It leads to definite predictions to the Higgs boson couplings to fermions and gauge bosons.

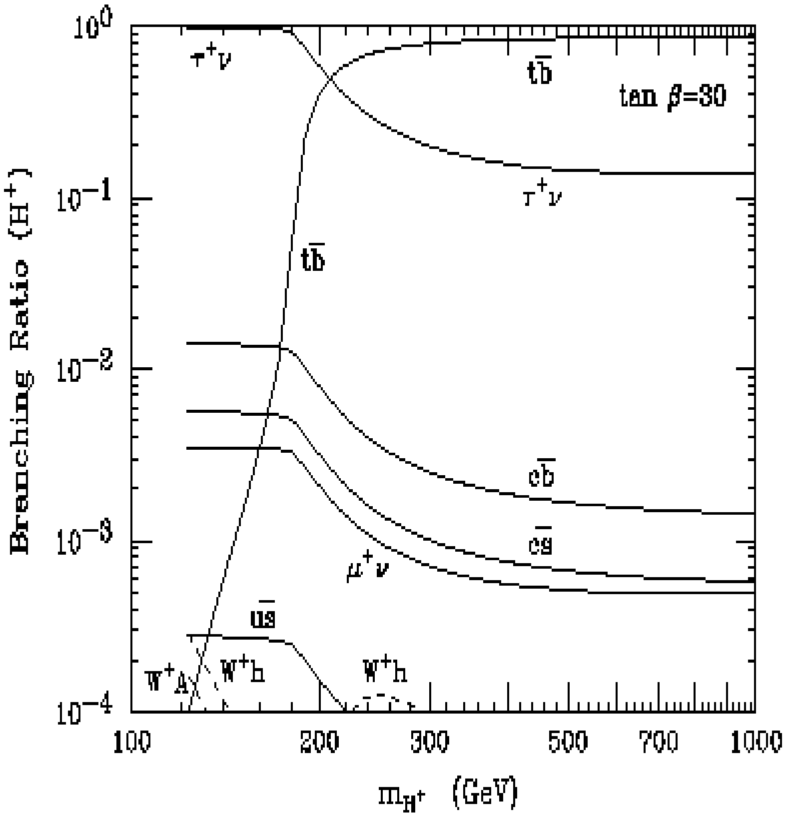
- Such couplings, however, are affected by radiative corrections induced by supersymmetric particle loops. It affects the searches for Higgs bosons at hadron and lepton colliders in an important way.

- Tau Lepton polarization is a powerful discriminative characteristic to separate charged Higgs signal

  →two representative scenarios with tH+b suppressed/enhanced couplings shown for ILC.

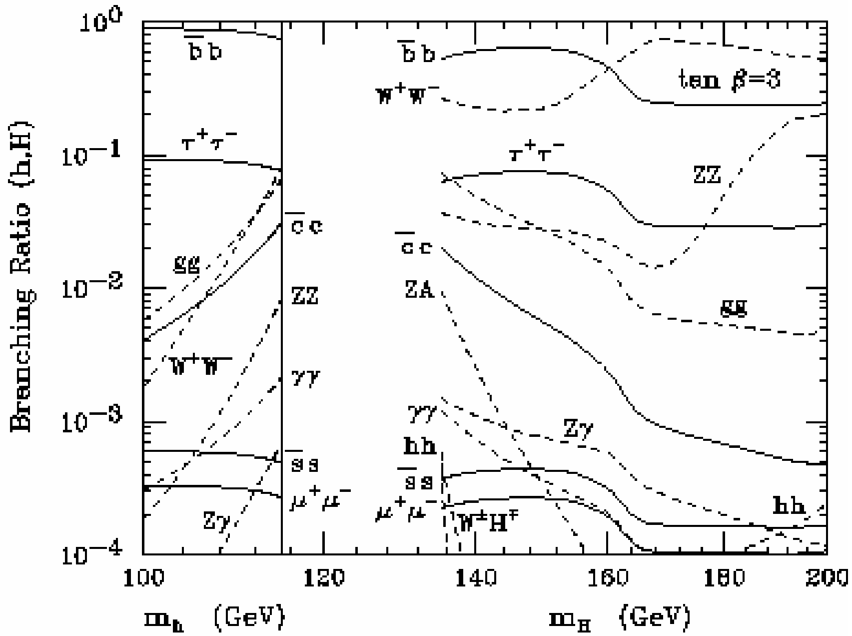
- Fit to pion spectra from polarized tau decays allows to extract light charged Higgs masses with $\delta m_{H^{\mp}} \approx 0.5 - -1\,\mathrm{GeV}$ (theoretical study, but only $P_\tau$ from $\tau^{\pm} \to \pi^{\pm} \nu_\tau$ used!)

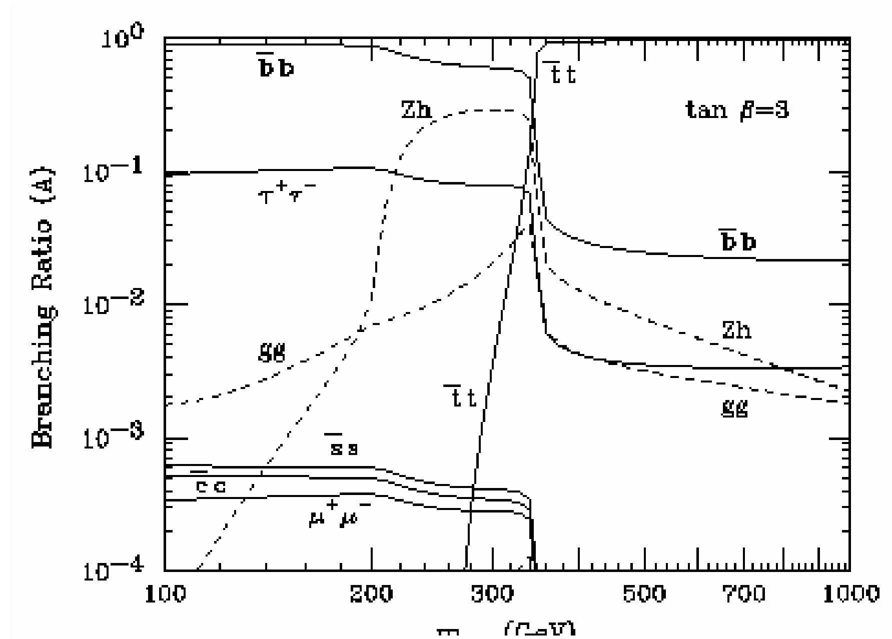
# Variation of BR($H^{+-}\rightarrow tb$) depending on parameter space

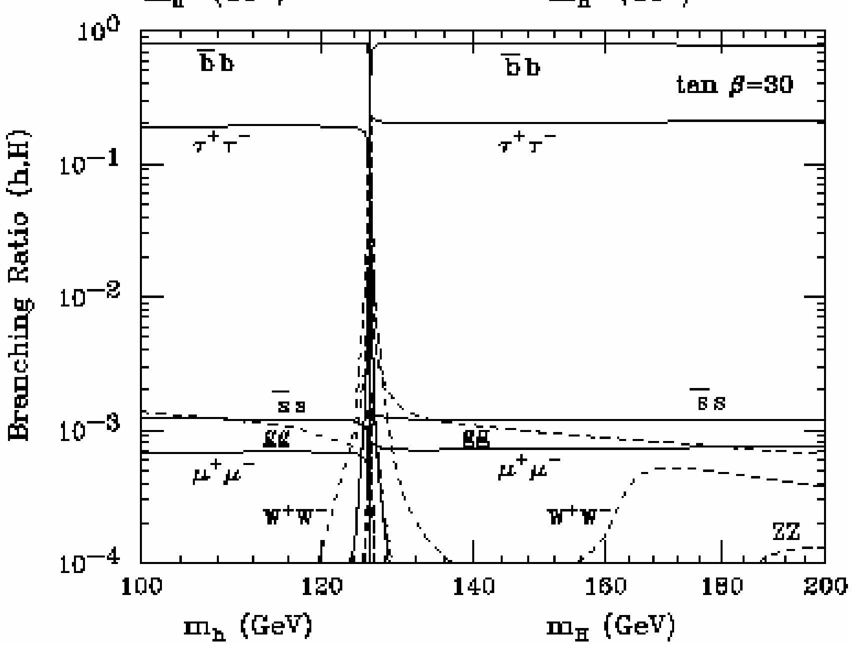


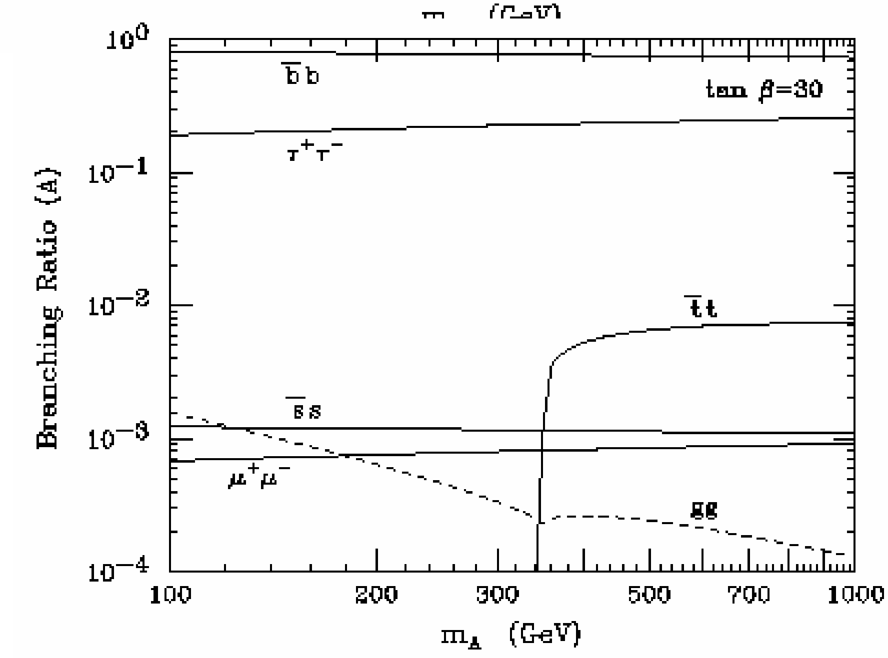
# Neutral MSSM Higgs Branching Ratios

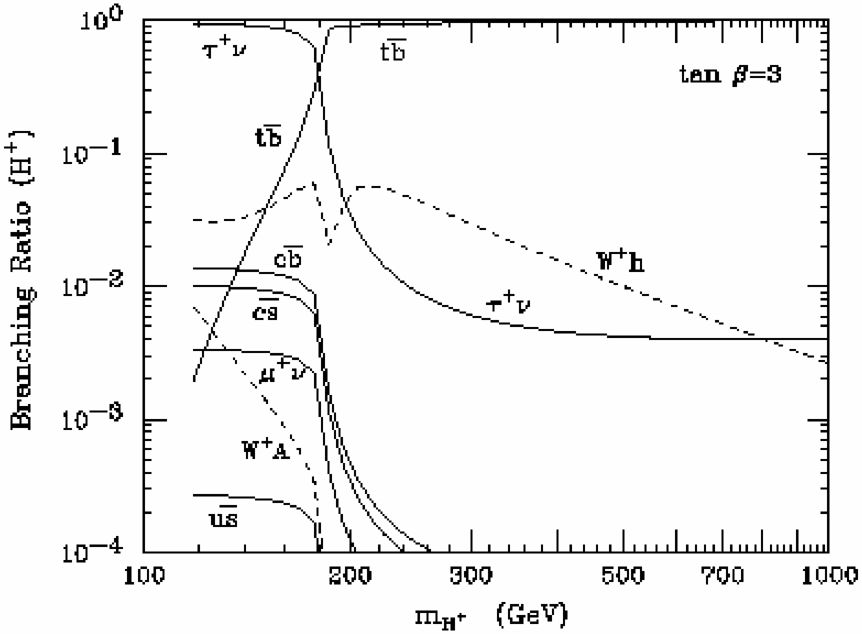
large $\tan\beta$ : $h, H, A$ to $b\bar{b}, \tau^+\tau^-$ dominate    low $\tan\beta$ : richer pattern

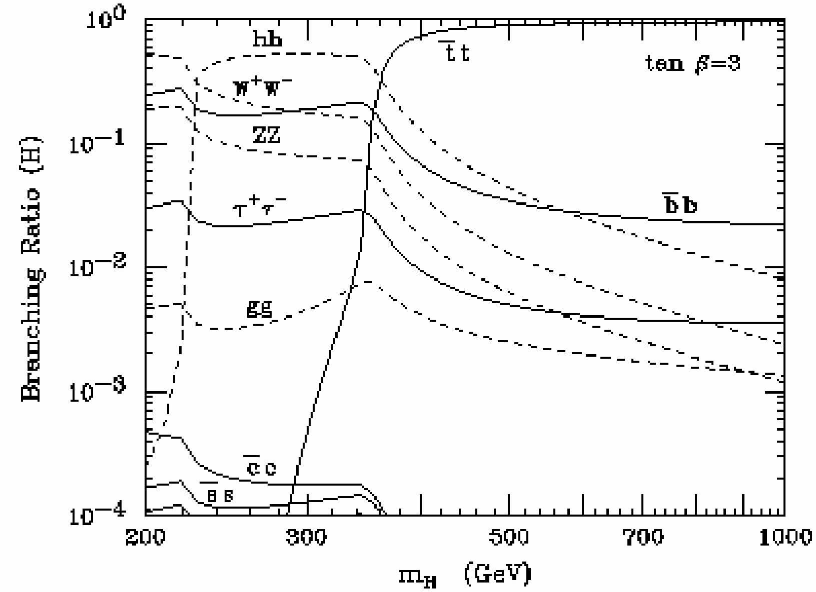


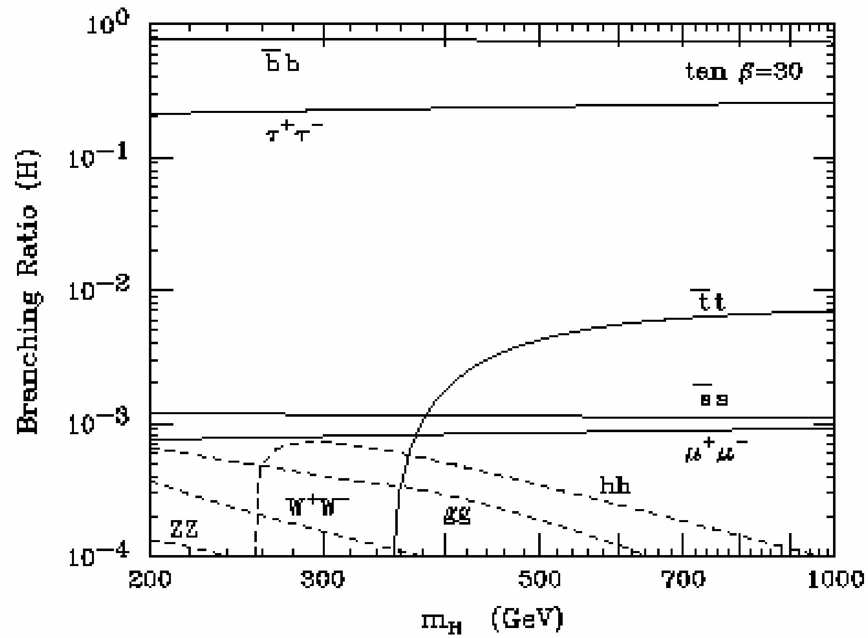



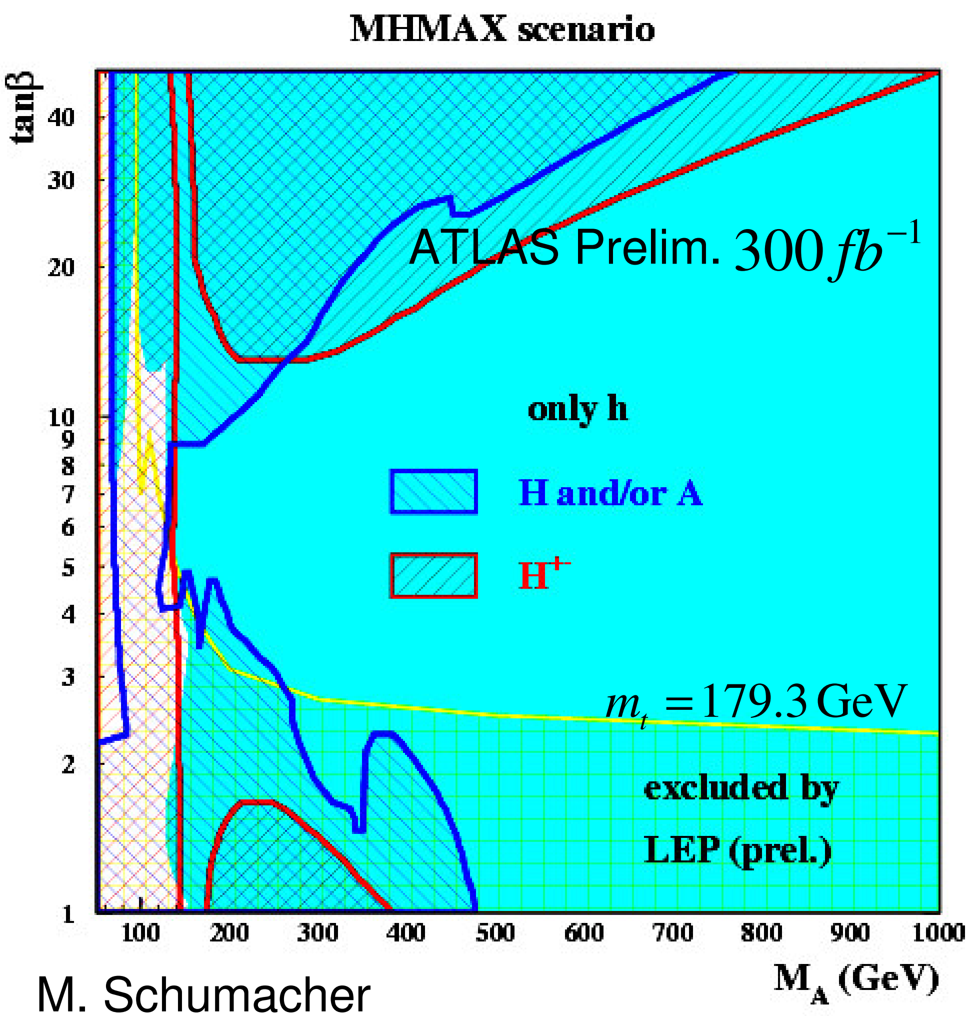




tan β=3
Branching Ratio (H+)
$m_{H^+}$ (GeV)
$\tau^+\nu$
$t\bar{b}$
$W^+h$
$c\bar{b}$
$c\bar{s}$
$\mu^+\nu$
$W^+A$
$u\bar{s}$


tan β=3
Branching Ratio (H)
$m_H$ (GeV)
hh
$\bar{t}t$
$W^+W^-$
ZZ
$\tau^+\tau^-$
$\bar{b}b$
gg
$\bar{c}c$
$\bar{s}s$


tan β=30
Branching Ratio (H)
$m_H$ (GeV)
$\bar{b}b$
$\tau^+\tau^-$
$\bar{t}t$
$\bar{s}s$
$\mu^+\mu^-$
hh
$W^+W^-$
gg
ZZ

# LHC Prospects for MSSM Higgs Discovery:



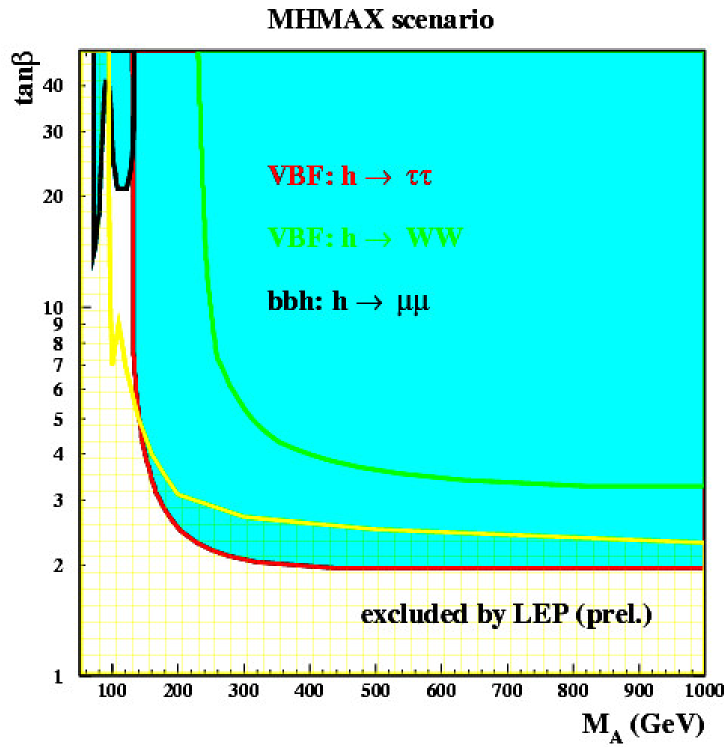

M. Schumacher

- **The whole parameter space can be covered by Higgs searches in the CP conserving MSSM already with 30 fb-1**
- Only the lightest Higgs can be discovered in a large area of MSSM parameter space
- Decay of h in different modes for one production channel may allow to measure ratios of decay rates and BR's

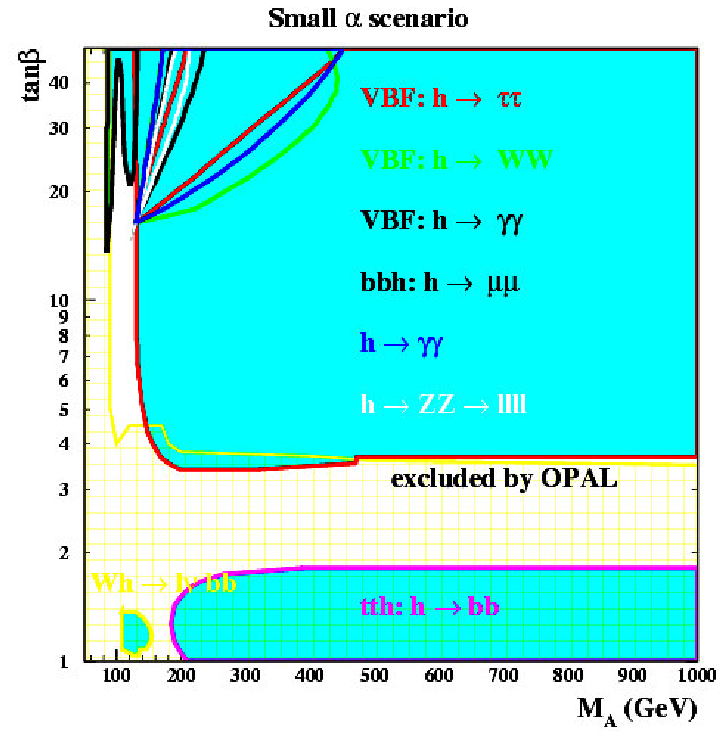
$$\text{VBF with } h, H \rightarrow WW, \tau^+\tau^-, \gamma\gamma; \quad gg \rightarrow \phi^0 \rightarrow \gamma\gamma, \mu\mu, \tau\tau, WW, ZZ$$

$$\phi^0 t\bar{t}(b\bar{b}) \text{ with } \phi^0 \rightarrow, b\bar{b}, \gamma\gamma(\mu\mu, \tau\tau); \quad gb(t\bar{t}) \rightarrow tH^\pm(\rightarrow \tau\nu(tb))$$

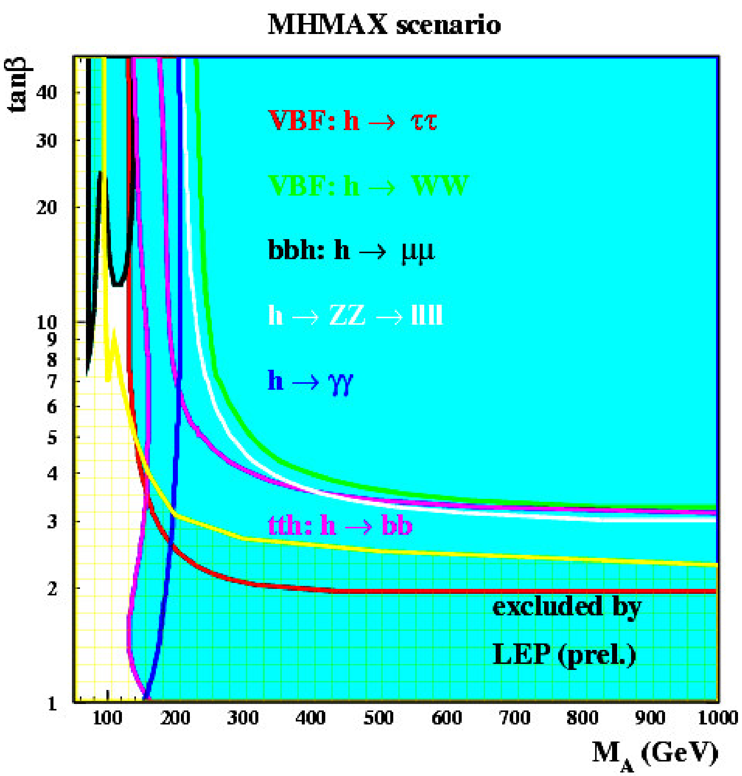
$$gg \rightarrow H/A \rightarrow t\bar{t}t\bar{t}, H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}, A \rightarrow Zh \rightarrow llb\bar{b}$$



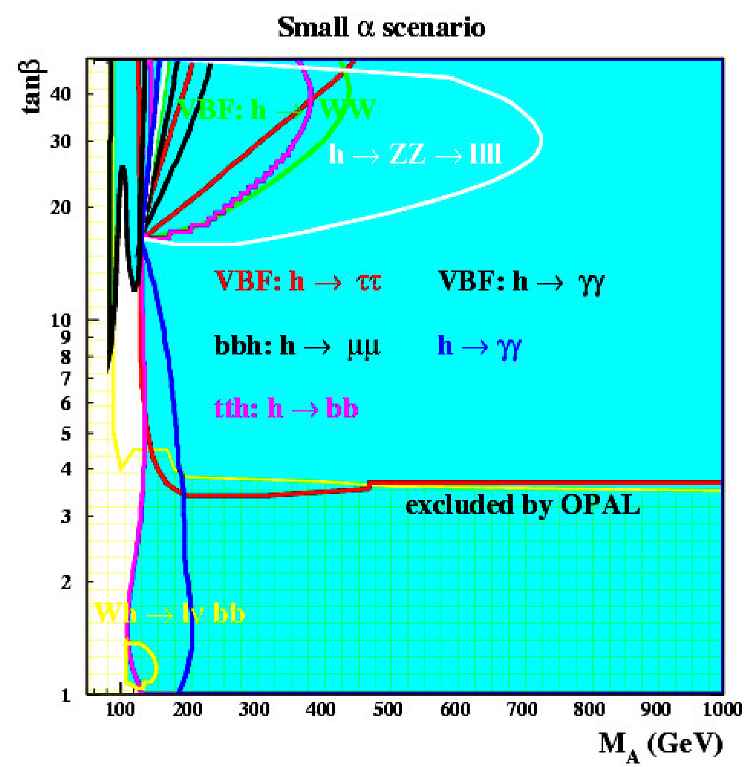

# ATLAS light higgs discovery reach




$30\,fb^{-1}$




$300\,fb^{-1}$




M. Schumacher'04

# CP Violation in the MSSM

- In low energy SUSY, there are extra CP-violating phases beyond the CKM ones, associated with complex SUSY breaking parameters

- One of the most important consequences of CP-violation is its possible impact on the explanation of the matter-antimatter asymmetry.

  Electroweak baryogenesis may be realized even in the simplest SUSY extension of the SM, but demands new sources of CP-violation associated with the third generation sector and/or the gaugino-Higgsino sector.

- These CP-violating phases may induce effects on observables such as new contributions to the e.d.m. of the electron and the neutron.

  However, effects on observables are small in large regions of parameter space

- In the Higgs sector at tree-level, all CP-violating phases, if present, may be absorbed into a redefinition of the fields.

- CP-violation in the Higgs sector appears at the loop-level, associated with third generation scalars and/or the gaugino/Higgsino sector, but can still have important consequences for Higgs physics

# Higgs Potential → Quantum Corrections

Minimization should be performed with respect to real and imaginary parts of Higgs fluctuations $H_1^0 = \phi_1 + iA_1$ $H_2^0 = \phi_2 + iA_2$

Performing a rotation: $A_1, A_2 \Longrightarrow A, G^0$ (Goldstone)

**Main effect of CP-Violation is the mixing of the three neutral Higgs bosons**

$$\begin{pmatrix} A \\ \Phi_1 \\ \Phi_2 \end{pmatrix} = \mathcal{O} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

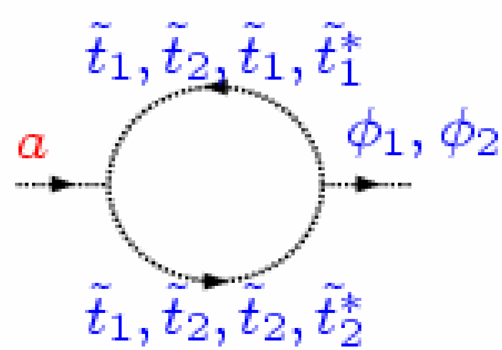
**In the base** $(A, \phi_1, \phi_2)$:

$$M_N^2 = \begin{bmatrix} \mathrm{m}_A^2 & (\mathrm{M}_{SP}^2)^T \\ \mathrm{M}_{SP}^2 & \mathrm{M}_{SS}^2 \end{bmatrix}$$

$M_{SS}^2$ is similar to the mass matrix in the CP conserving case, and $M_A^2$ is the mass of the would-be CP-odd Higgs.

$\mathrm{M}_{SP}^2$ **gives the mixing between would-be CP-odd and CP-even sates, predominantly governed by stop induced loop effects**

$$\mathrm{M}_{SP}^2 \propto \frac{\mathrm{m}_t^4}{16\pi^2 \mathrm{v}^2} \mathrm{Im}\left(\frac{\mu A_t}{\mathrm{M}_S^2}\right)$$




Gluino phase relevant at two-loop level. Guagino effects may be enhanced for large tan beta

# Interaction Lagrangian of W,Z bosons with mixtures of CP even and CP odd Higgs bosons

$$
\begin{aligned}
g_{H_i VV} &= \cos\beta\, \mathcal{O}_{1i} + \sin\beta\, \mathcal{O}_{2i} \\
g_{H_i H_j Z} &= \mathcal{O}_{3i}\,(\cos\beta\, \mathcal{O}_{2j} - \sin\beta\, \mathcal{O}_{1j}) - \mathcal{O}_{3j}\,(\cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i}) \\
g_{H_i H^- W^+} &= \cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i} + i\mathcal{O}_{3i}
\end{aligned}
$$

$(V = W, Z)$

$\mathcal{O}_{ij} \longrightarrow$ analogous to $\sin(\beta-\alpha)$ & $\cos(\beta-\alpha)$

→ All couplings as a function of two: $g_{\mathrm{H_k VV}} = \varepsilon_{ijk}\; g_{\mathrm{H_i H_j Z}}$

and sum rules: $\sum_{i=1}^{3} g^2_{H_i ZZ} = 1$ $\quad \sum_{i=1}^{3} g^2_{H_i ZZ}\, m^2_{H_i} = m^{2,\max}_{H_1} \lesssim 135$ GeV

*(equiv. to CP-conserv. case)*

upper bound remains the same

Decoupling limit: $m_{H^+} \gg M_Z$

- **Effective mixing between the lightest Higgs and the heavy ones is zero**

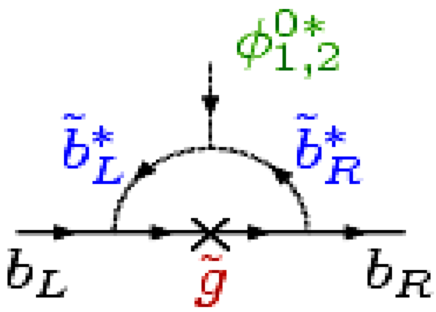
**➔ $H_1$ is SM-like**

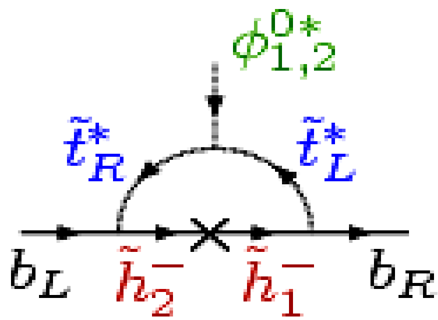
- **Mixing in the heavy sector still relevant !**

$$
\longrightarrow \begin{pmatrix} m_A^2 & \Delta \\ \Delta & \Delta' + m_A^2 \end{pmatrix} \qquad \mathrm{w/} \qquad \Delta \sim \mathcal{O}(\Delta') \ll m_A^2
$$

# Yukawa Couplings: CP violating vertex effects

$$-\mathcal{L}^{\rm eff}_{\phi^0\bar{b}b} = (h_b + \delta h_b)\,\phi_1^{0*}\,\bar{b}_R b_L + \Delta h_b\,\phi_2^{0*}\,\bar{b}_R b_L \;+\; \text{h.c.}$$




coupling $\Delta h_b$ generated by SUSY breaking effects

$$\frac{\delta h_b}{h_b} \sim -\frac{2\alpha_s}{3\pi}\frac{m^*_{\tilde{g}} A_b}{\max\left(Q_{\tilde{b}}^2, |m_{\tilde{g}}|^2\right)} - \frac{|h_t|^2}{16\pi^2}\frac{|\mu|^2}{\max\left(Q_{\tilde{t}}^2, |\mu|^2\right)}$$

$$\frac{\Delta h_b}{h_b} \sim \frac{2\alpha_s}{3\pi}\frac{m^*_{\tilde{g}}\mu^*}{\max\left(Q_{\tilde{b}}^2, |m_{\tilde{g}}|^2\right)} + \frac{|h_t|^2}{16\pi^2}\frac{A^*_t\mu^*}{\max\left(Q_{\tilde{t}}^2, |\mu|^2\right)}$$

- The one loop effects to the Yukawa couplings introduce CP-violating effects which are independent of the Higgs mixing

the phase of the superfield $b_R$ is real and positive:

$$h_b = \frac{g_w m_b}{\sqrt{2}M_W \cos\beta\,[\,1 + \delta h_b/h_b + (\Delta h_b/h_b)\tan\beta\,]}$$

# Higgs boson-quark Lagrangian

- **taking into account both CP-violating self-energy and vertex effects**

(similar vertex effects in the up quark sector, but no tan $\beta$ enhancement)

$$L_{\mathrm{Hf\bar{f}}} = -\sum_{i=1}^{3} \mathrm{H_i}[(g_{\mathrm{W}} m_{\mathrm{d}} / 2\mathrm{M_W})\, \bar{\mathrm{d}}\, (\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i dd}} + \mathrm{g}^{\mathrm{P}}_{\mathrm{H_i dd}}\, \gamma_5)\, \mathrm{d}$$

$$+ (g_{\mathrm{W}} m_{\mathrm{u}} / 2\mathrm{M_W})\, \bar{\mathrm{u}}\, (\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i uu}} + \mathrm{g}^{\mathrm{P}}_{\mathrm{H_i uu}}\, \gamma_5)\, \mathrm{u}]$$

**with:**

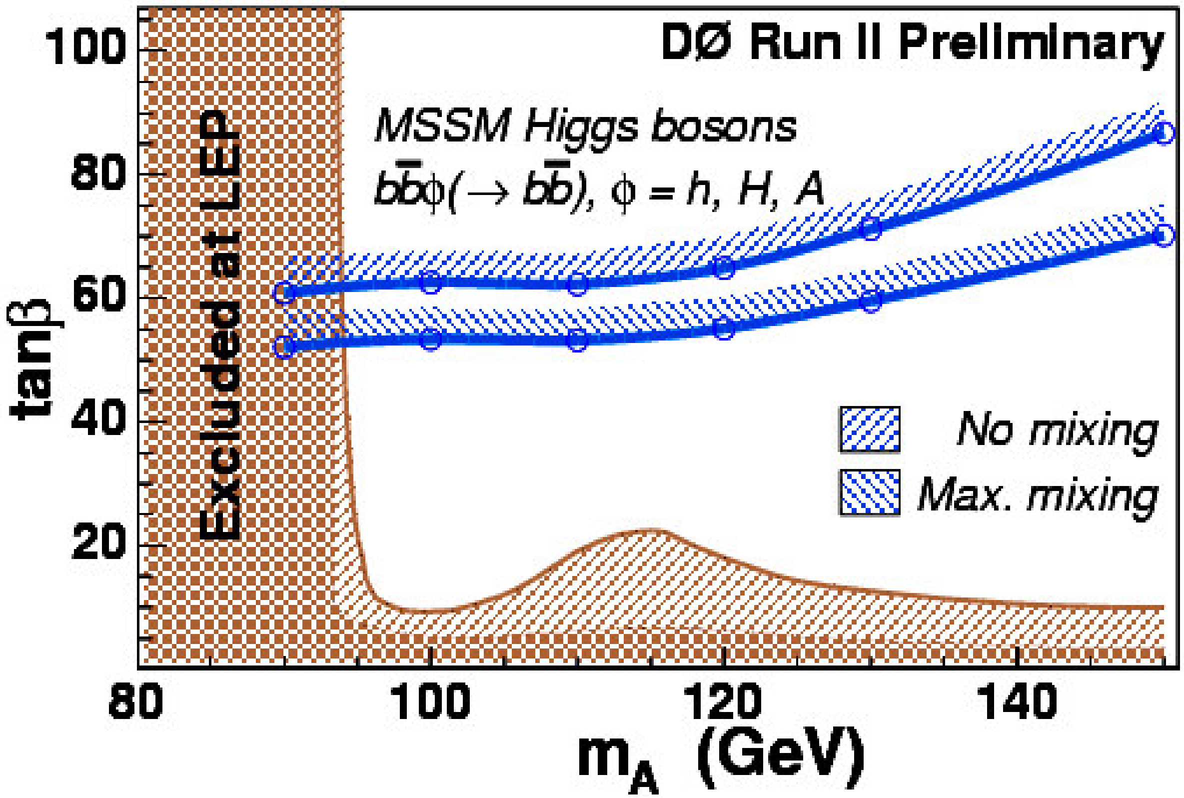
$$\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i dd}} = \frac{1}{h_b + \delta h_b + \Delta h_b \tan\beta} \Big\{ \mathrm{Re}(h_b + \delta h_b) \frac{O_{1i}}{\cos\beta} + \mathrm{Re}(\Delta h_b) \frac{O_{2i}}{\cos\beta}$$

$$- \big[ \mathrm{Im}(h_b + \delta h_b) \tan\beta - \mathrm{Im}(\Delta h_b) \big] O_{i3} \Big\}$$

$$\mathrm{g}^{\mathrm{P}}_{\mathrm{H_i dd}} = \frac{1}{h_b + \delta h_b + \Delta h_b \tan\beta} \Big\{ \big[ \mathrm{Re}(\Delta h_b) - \mathrm{Re}(h_b + \delta h_b) \tan\beta \big] O_{31}$$

$$- \mathrm{Im}(h_b + \delta h_b) \frac{O_{1i}}{\cos\beta} - \mathrm{Im}(\Delta h_b) \frac{O_{2i}}{\cos\beta} \Big\}$$

# Present Tevatron reach in the CP conserving MSSM Higgs sector




$200\,\mathrm{pb}^{-1}$

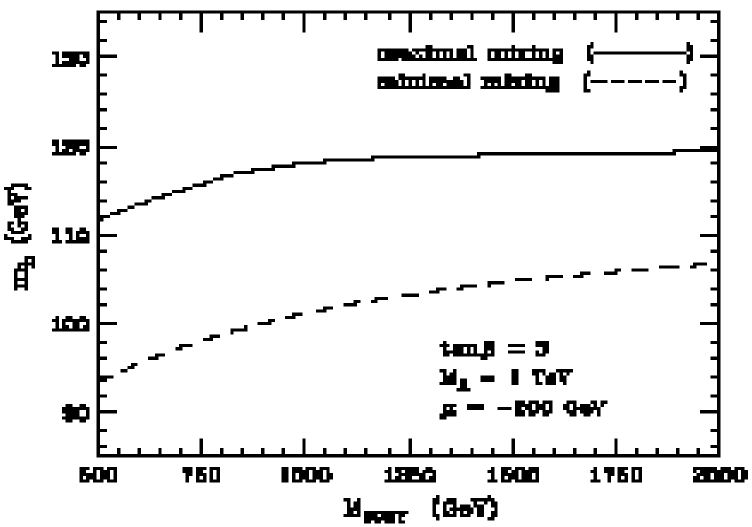
$$p\bar{p} \rightarrow \phi b\bar{b} \rightarrow b\bar{b}b\bar{b} \text{ with}$$

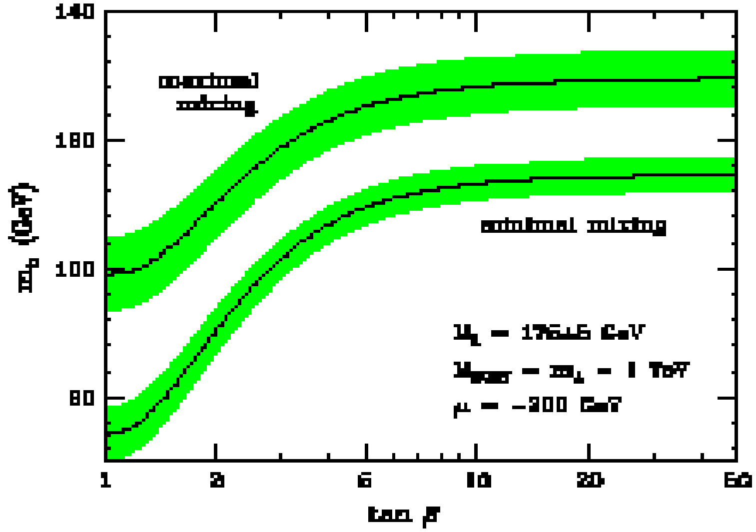
$$\phi = \mathrm{A/h} \text{ or } \mathrm{A/H}$$

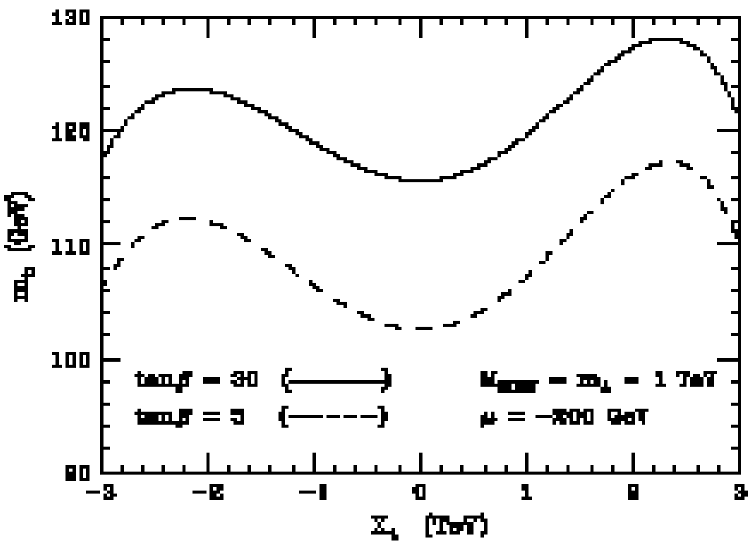
With about 5 fb-1 one can expect to test the regime with:

$$\tan\beta \approx 10 \text{ and } \mathrm{m_A} \approx 100\,\mathrm{GeV} \;---\; \tan\beta \approx 50 \text{ and } \mathrm{m_A} \approx 250\,\mathrm{GeV}$$

# *main effects already present in one-loop formulae*







- $m_t^4$ enhancement
- logarithmic sensitivity to $m_{\tilde{t}_i}$
- depend. on $\tilde{t}$-mixing $X_t$

  $\Longrightarrow$ max. value $X_t \sim \sqrt{6} M_S$

  (scheme depend.) small asym. at h.o.

M.C. & Haber

$M_{SUSY} \equiv M_Q = M_U = M_D$ if $M_{SUSY} \gg m_t \rightarrow M_S^2 \simeq M_{SUSY}^2$

- at 2 loops $\longrightarrow M_{\tilde{g}}$ dependence

# Radiative corrections to Higgs Masses

important quantum correc. due to loops of particles and their superpartners:
incomplete cancellation due to SUSY breaking $\Longrightarrow$ main effects: top and stop loops;
bottom and sbottom loops in large $\tan\beta$ regime

The stop mass matrix:

$$\begin{pmatrix} M_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & M_U^2 + m_t^2 + D_R \end{pmatrix}$$

$D_L \equiv (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) M_z^2 \cos 2\beta$ and
$D_R \equiv \frac{2}{3}\sin^2\theta_W M_z^2 \cos 2\beta$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2 M_W^2}\left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \text{h.o.}$$

$M_S^2 = \frac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2)$ and $X_t = A_t - \mu/\tan\beta \longrightarrow$ stop mixing

- two-loop log. and non-log.effects are numerically important $\rightarrow$ computed by different methods:

  - diagrammatic
  - effective potential
  - RG-improved effective potential

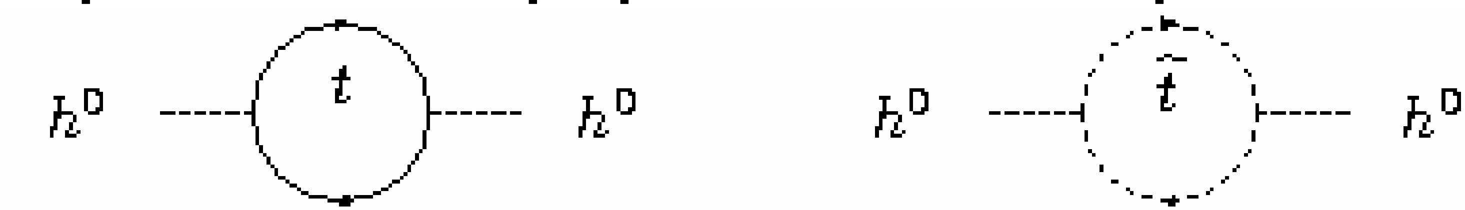
- upper limit on Higgs mass:

  $m_h \lesssim 135$ GeV

$M_S = 1 \rightarrow 2$ TeV $\Longrightarrow \Delta\, m_h \simeq 2 - 5$ GeV
$\Delta\, m_t = 1$ GeV $\Longrightarrow \Delta\, m_h \sim 1$ GeV

- **Supersymmetric relations between couplings imply** $m_h \le m_Z$

**After quantum corrections, Higgs mass shifted due to incomplete cancellation of particles and superparticles in the loops**



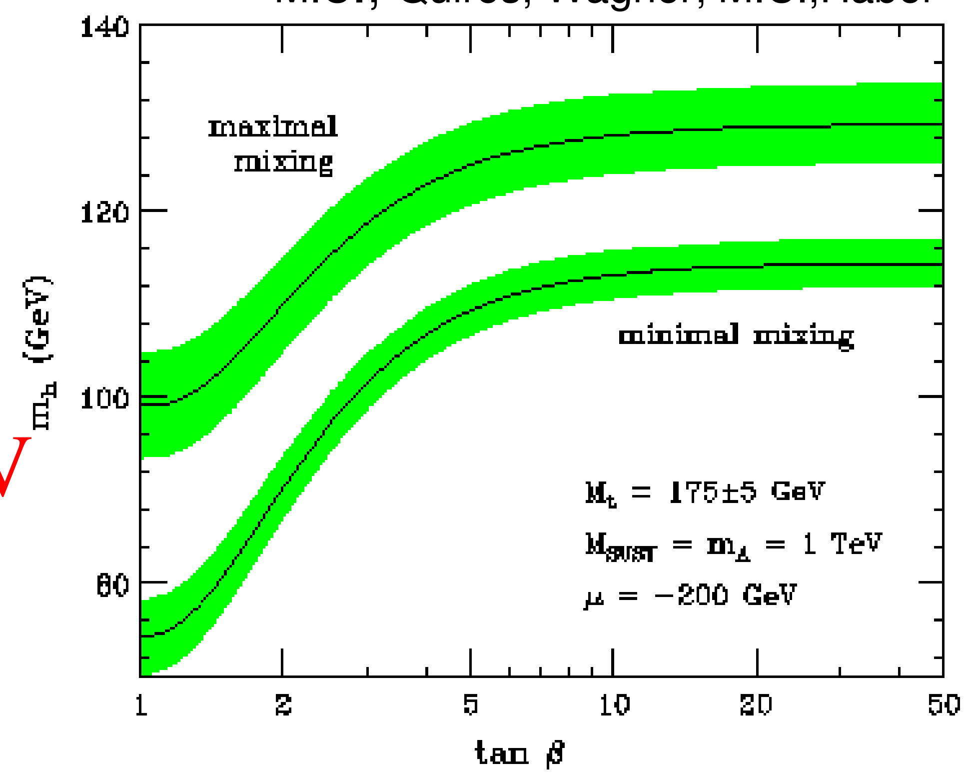

**Main Quantum effects**: $m_t^4$ enhancement ; dependence on the stop mixing $X_t$ ; logarithmic sensitivity to the stop mass (averaged: $M_S$ )

**Upper bound :**

$$m_h \le 135\,\text{GeV}$$

**stringent test of the MSSM**

M.C., Quiros, Wagner; M.C.,Haber

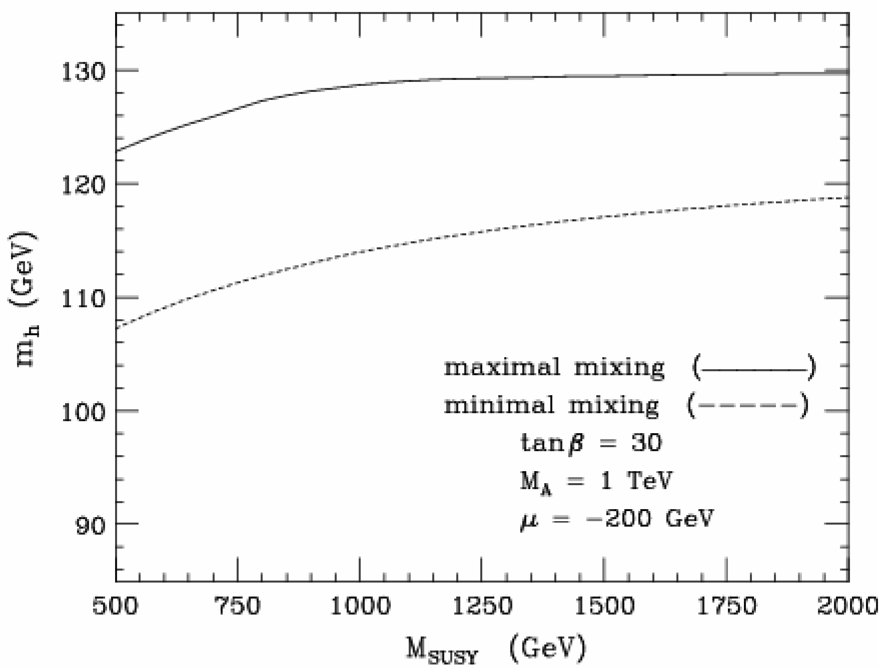



## LEP MSSM HIGGS limits:

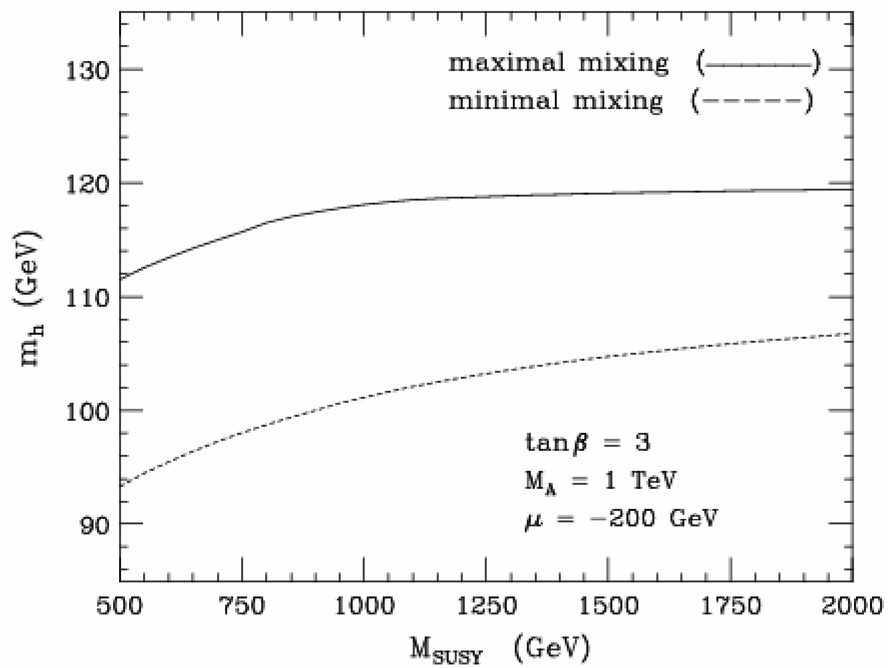
$$m_h > 91.0\text{GeV};\, m_A > 91.9\text{GeV}$$

$$m_{H^\pm} > 78.6\text{GeV}$$

$$m_h^{\text{SM-like}} > 114.6\text{GeV}$$



maximal mixing (———)
minimal mixing (- - - - -)
tan β = 30
M_A = 1 TeV
μ = −200 GeV
m_h (GeV)
M_SUSY (GeV)
90
100
110
120
130
500
750
1000
1250
1500
1750
2000

maximal mixing (———)
minimal mixing (- - - - -)
tan β = 3
M_A = 1 TeV
μ = −200 GeV
m_h (GeV)
M_SUSY (GeV)
90
100
110
120
130
500
750
1000
1250
1500
1750
2000